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Proprietary parts as a secondary market strategy

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A B S T R A C T

Introducing proprietary parts to gain a competitive edge is a well-known, yet poorly understood strategy original equipment manufacturers (OEMs) adopt. In this paper, we consider an OEM who sells new products and competes with an independent remanufacturer (IR) selling remanufactured products. The OEM contemplates proprietary parts to manage the secondary market for remanufactured products. Thereby, the OEM designs its product to balance the trade-off between the cost of proprietariness and the extra income from selling the proprietary spare parts to the IR. Deterring market entry by the IR through prohibitively pricing the proprietary spare parts, an OEM strategy observed in several industries, is only optimal when the willingness-to-pay for remanufactured products is low. Otherwise, the OEM benefits more from sharing the secondary market profits with the IR through the use of proprietary parts. Finally, we find that the OEM can also use proprietary parts to strategically deter entry by the IR, discouraging her from collecting cores. This can support the OEM's decisions to engage in remanufacturing even in the case of a collection cost disadvantage. While the introduction of proprietary parts is detrimental to both IRs and consumers, we show that for consumers such loss is reduced when the OEM engages in product remanufacturing.

1. Introduction

Remanufacturing is the process whereby used products are collected and brought back to their original cosmetic and functional conditions (Thierry, Salomon, Van Nunen, & Van Wassenhove, 1995). The remanufacturing business is worth billions of dollars worldwide and is relevant to a considerable number of industrial sectors (Hagerty & Glader, 2011; Stindt et al., 2017; Sundin & Dunbäck, 2013). Remanufacturing is carried out by either the original equipment manufacturer that also builds the new product (henceforth referred to as the OEM or 'he') or by independent remanufacturers (IR or 'she'). OEMs frequently see the existence of IRs as a menace, due to the widely accepted belief that remanufactured products are in direct competition with their new counterparts (Ferguson & Toktay, 2006; Guide & Li, 2010).

> "I think that they see us as another competitor, that customers who buy refurbished items, they will not buy new ones." (Independent remanufacturer A, on the relationships between OEMs and IRs)[1]

OEMs also believe that poorly remanufactured products can lead to brand damage (Guide, Harrison, & Van Wassenhove, 2003), and see little benefit in collaborating with IRs.

> "[...] if a customer chooses non-AirFlight[2] parts, we will probably write to the customer and say that we cannot take responsibility for the quality [of the product]." (Aerospace OEM engaged in B2B)

This quote draws attention to a strategy many OEMs use to control the aftermarket of their products, namely the introduction of proprietary spare parts. A part is said to be proprietary if the manufacturer holds the design rights. Examples, among many

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[1] Unless otherwise stated, all quotes in this paper are from interviews and personal communications with the company representatives.
[2] Fictitious name.

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0377-2217/

others, include Satair for Airbus Spare parts[3] or LG for white goods[4]. Introducing proprietary parts increases the control the OEM exerts over the marketing and sales of spare parts, and consequently, the power over the supply chain of remanufactured products. In some cases, OEMs refuse to supply parts to non-authorized repair shops, seek legal action against anyone modifying and repairing their products or increase the prices of proprietary spare parts to a point where remanufacturing becomes economically infeasible (Brandom, 2015; Dayen, 2015; Koebler, 2018; Matchar, 2016). This may force remanufacturers to consider other strategies for sourcing spare parts.[5] To prevent the IR from doing so, the OEM chooses parts to be proprietary that have a high failure rate. Such practices are applied in the electronics industry (McAllistair, 2013), in automotive manufacturing (Solon, 2017), and the white goods industry as the following quote suggests:

> "I would guess over 90% of frost-free [fridges] fail because of electronics. [...] New boards are simply too expensive as they have to be bought from the manufacturer. The fridges are still collected and are in demand because they look modern. Who on a low income wouldn't want one? The vast majority go for scrap recycling." (Independent remanufacturer B)

This quote also highlights two other aspects. First, it suggests that the use of proprietary parts affects society in general. It limits consumer choice and contributes to the escalating volume of products that are discarded every year, and that could be otherwise diverted from the landfill to the secondary market. Second, it ignores potential revenues from the sales of spare parts to be used in the remanufacturing process that might outweigh the demand cannibalization effect.

In summary, introducing proprietary parts is a strategy for the OEM to control the secondary market of used products and revenue from the sales of spare parts. However, it is less obvious how to implement it. Thus, our first research question is:

- What is the OEM's optimal market strategy when introducing proprietary parts?

This question captures explicitly whether the OEM should use proprietary parts to preempt the secondary market or to extract extra profits from it. Since the control over the secondary market through the use of proprietary parts comes at a price, our second research question is:

- Under what conditions does the introduction of proprietary parts pay off for the OEM?

Without proprietary parts, the OEM accepts the potential entry of an IR and consequently, the profit decreases due to competition between the new and remanufactured products. The OEM also foregoes the potential profits accrued from the sales of spare parts. Both aspects must be traded-off against the design and (re-) manufacturing cost of proprietary parts.

Using proprietary parts also has a side-effect that may be used by the OEM to his own benefit. Large, multinational, OEMs often find it difficult to compete with local IRs in collecting cores. Even without the fear of demand cannibalization, this serves as a barrier to OEM remanufacturing. In such a context, the OEM can use proprietary parts to obtain exclusive access to the cores, by making the secondary market unprofitable for the IR. Having removed this collection barrier, the OEM may then find it profitable to engage in remanufacturing. This leads to our third research question:

- Under what conditions should the OEM prefer in-house remanufacturing over IR remanufacturing after introducing proprietary parts?

To answer our research questions, we use a stylized model combining new product and proprietary parts pricing decisions of the OEM with remanufactured product pricing decisions of the IR. We model the proprietariness decision of the OEM by considering the product design as well as (re-)manufacturing cost implications of introducing proprietary parts.

A first key insight is that – given proprietary parts are used – pre-empting the secondary market should only be the preferred option when consumers' willingness-to-pay for remanufactured products is low. Otherwise, sales revenues from proprietary parts outweigh the profit reduction on the primary market due to demand cannibalization. This insight complements the existing literature, which argues that demand cannibalization of new by remanufactured products may be less of an issue for OEMs than they expect, as the loss in revenue due to cannibalization is compensated by the secondary market (Atasu, Guide, & Van Wassenhove, 2010; Guide & Li, 2010).

Our second key insight is that even if it is possible and optimal from the OEM's point of view to deter the entry of an IR through new product pricing when there are no proprietary parts, introducing proprietary parts may be a better strategy. In doing so, the OEM can stick to his monopolist's new product price and control the entry threat by the IR on the secondary market purely by adjusting proprietary spare parts' price.

Our third key insight is that, counter to the findings from the extant literature, the OEM may engage in remanufacturing in situations where the IR would not. Previous work found that the IR, who does not have a stake in the primary market, faces lower hurdles to enter the secondary market than the OEM. This may be magnified if the IR has a collection cost advantage due to more local involvement and therefore easier access to cores than a global OEM. The present paper extends this literature by adding the manufacturing cost component into the argument. Given the mark-up the OEM charges for his proprietary parts, the IRs remanufacturing cost is higher than the OEMs remanufacturing cost. We find that this remanufacturing cost advantage may outweigh the primary market profit decrease due to demand cannibalization and make OEM remanufacturing worthwhile if the OEM can overcome the collection access issue. Here the proprietary parts serve as the lever, as prohibitively pricing them discourages the IR to enter the market and collect cores, leaving the OEM without competition.

The remainder of this paper is organized as follows. In Section 2 we place our work within and highlight our contributions to the existing literature. Section 3 captures our base model and analysis of the non-remanufacturing OEM, while Section 4 presents the extension focusing on OEM remanufacturing. Finally, Section 5 concludes our paper.

2. Literature review

Remanufacturing and closed-loop supply chain management have been extensively studied in the past decades. Comprehensive literature reviews can be found in Souza (2013) and Govindan, Soleimani, and Kannan (2015). Atasu (2016) integrated the latest and most influential research in an edited book. Our study builds on two specific streams within the CLSC literature: market segmentation and competition between new and remanufactured products, as well as product design.

[3] http://www.satair.com/products/airbus-proprietary-parts.

[4] https://www.lg.com/us/support/lg-direct-service/parts-and-accessories.

[5] A commonly applied approach is to scavenge parts from used units. Note, however, that because extra cores need to be collected and in some occasions purchased, and labor is employed, scavenged parts are not for free. Besides, scavenging parts creates additional complexities and even delays to the remanufacturing process, as remanufacturers might need to wait for similar products to the one being remanufactured.

2.1. Market segmentation and competition in CLSCs

Market segmentation and competition have been recognized as essential strands of research on CLSCs. Majumder and Groenevelt (2001) and Ferrer and Swaminathan (2010) addressed the competition between an OEM and an IR and considered the volume of returns as, respectively, a fraction of the products sold (and therefore an exogenous variable) and as having a linear relationship with collection effort. Atasu, Sarvary, and Van Wassenhove (2008) proposed an alternative approach to modeling competition and contributed to prior research by incorporating green segments, OEM competition, and examining product life-cycle effects, while Örsdemir, Kemahlıoğlu-Ziya, and Parlaktürk (2014) considered the impact that quality has on the competition between the OEM and the IR. Adding a supply chain stage by integrating a supplier providing a critical component required for both manufacturing and remanufacturing, Jin, Nie, Yang, and Zhou (2017) and later Wu and Zhou (2019) showed that IR remanufacturing could increase the OEM's profit. In this setting, the supplier might be inclined to lower the wholesale price of the component to increase both sales of new products and returns to be remanufactured.

Others have examined competition in the primary market, and how it affects the collection strategy. Heese, Cattani, Ferrer, Gilland, and Roth (2005), e.g., studied the case where an OEM both manufactures and remanufactures products (i.e., hospital beds) and competes with another OEM. Kumar Jena and Sarmah (2014) considered the case of two OEMs competing at both primary and secondary markets. Wu and Zhou (2017) extended the work of Savaskan, Bhattacharya, and Van Wassenhove (2004) by examining the effect of competition in the primary market (the market for new products) in product recovery decisions. In the presence of a group of newness-conscious consumers, Wu and Zhou (2016) did show how two competing OEMs can benefit from third-party remanufacturing.

Some papers explicitly addressed OEM strategies to control the secondary market. For example, Ferguson and Toktay (2006) studied an OEM that preemptively collects cores without actually remanufacturing them. Oraiopoulos, Ferguson, and Toktay (2012) studied relicensing of software in the IT sector as a means to benefit from the secondary market, as consumers buying refurbished hardware from an IR also must purchase a license for a bundled software from the OEM. Finally, Hong, Govindan, Xu, and Du (2017) considered competitive settings where the IR is granted permission to apply remanufacturing technology from the OEM. They analyzed different types of licensing agreements between OEM and IR.

Essentially, this stream of literature examined how OEMs compete with IR and other OEMs and focused mostly on pricing decisions. Moreover, it was usually assumed that the technology and product design were exogenously given and did not change during the decision horizon. The last two papers, Oraiopoulos et al. (2012) and Hong et al. (2017), came closest to our setting in studying a mechanism for the OEM to benefit from the secondary market. However, in both papers, it is assumed that product design is fixed, and licensing does not incur any cost for the OEM. Moreover, in Oraiopoulos et al. (2012) the licensing interaction takes place between the OEM and the consumer directly, while in our model, like in Hong et al. (2017), the proprietary parts (license) have to be bought by the IR.

2.2. Product design

Product design has different dimensions, and several of them have been studied in the past in the context of CLSCs. A stream of literature focuses on demand-inducing product design and its interaction with used product recovery. Atasu and Souza (2013) investigated how product reuse impacts product quality choice and found that recovery may lead to higher product quality. They also showed how the form of product recovery, recovery cost structure, and product take-back legislation affects a firm's quality choice. Örsdemir et al. (2014) extended this work to the oligopoly setting and studied the competitive quality choice in the presence of remanufacturing. They found that when an OEM competes with an IR, remanufacturing may reduce quality and increase environmental impact.

Another sub-field of research has examined design choices affecting remanufacturability and the cost of remanufacturing. Debo, Toktay, and Van Wassenhove (2005) studied the joint pricing and remanufacturability decision faced by a manufacturer introducing a remanufacturable product. If a firm can decide on product quality and remanufacturability levels, it will couple increased remanufacturing with higher product quality, as shown in Gu, Chhajed, Petruzzi, and Yalabik (2015). Wu (2012) studied the design-for-disassembly problem in a supply chain formed by an OEM producing only new products and an IR. Using a two-period model, the author found that the optimal level of disassemblability crucially depends on the recovery costs of the used products. When recovery costs are low, the OEM chooses low levels of disassemblability to discourage competition by the IR. These papers are related to our setting in that the introduction of proprietary parts by the OEM also affects the remanufacturing cost for the IR. However, in none of these papers does the design decision yield direct benefits on the secondary market for the OEM.

2.3. Summary of the contributions of our work to this literature

Our paper builds on and contributes to the above streams of research within the CLSC field in two ways. First, by considering the use of proprietary parts which — different than software licenses — incur a cost for the OEM both in designing them as well as in embedding them in new (and remanufactured) products, we model different market environments (e.g., white goods, heavy machinery). Second, we also contribute to the understanding of an OEM's optimal decisions under such costly action to control the secondary market. This decision essentially complements our understanding of the mechanisms that can be deployed to manipulate remanufacturing costs. Different from the papers focusing on remanufacturability or design-for-disassembly, we model a setting where the design choice, i.e., the introduction of proprietary parts, is used by the OEM to benefit directly from IR remanufacturing. Both OEM and IR, in this case, adopt a coopetition strategy, where the IR acts as both competitor and buyer. This complements our understanding of situations (see, e.g., Jin et al., 2017; Wu & Zhou, 2016; 2019) under which third party remanufacturing can be beneficial to the OEM.

3. The case of a non-remanufacturing OEM

To study the questions posed in the introduction, we use a stylized model of an OEM offering new products only and an independent manufacturer (IR), which may compete with the OEM by remanufacturing used products. The environment in which both competitors operate is described in Section 3.1. Then, we – in turn – derive and discuss the structure of the optimal market decisions of both the OEM and the IR under generic parts only (in Section 3.2) as well as under proprietary parts (in Section 3.3). A comparison of the two cases and a discussion of their structural differences is put forth in Section 3.4. Using a comprehensive numerical study, we also quantify the economic impact of using proprietary parts for a broad set of possible scenarios.

3.1. Model description

Setting. Since our focus is on the competition between the OEM and the IR, we assume – in line with prior research – a monopolist OEM on the market for new products (Atasu, Toktay, & Van Wassenhove, 2013; De Giovanni & Zaccour, 2014; Savaskan et al., 2004). We assume a mature market and thus consider a single period in a steady-state setting, where a period corresponds to the usage period of the product (Abbey, Kleber, Souza, and Voigt, 2017; Atasu and Souza, 2013, see, e.g.,). At the end of the period, a fraction γ of the new units sold at a price p_n becomes available for collection and subsequent remanufacturing, as in Esenduran, Kemahlıoğlu-Ziya, and Swaminathan (2017) and Ferrer and Swaminathan (2006).

We also assume, as a starting point, that the OEM is currently not engaged in remanufacturing his end-of-use products. Reasons for that could be resource-based, like the absence of a logistical collection network (Stindt et al., 2017), or demand-based, such as fear of cannibalization of new product sales (Guide & Li, 2010). While the OEM does not collect and remanufacture himself, he realizes the threat of an IR entering the secondary market. In light of that threat, the OEM considers redesigning his products using proprietary parts. Being proprietary, these parts cannot be remanufactured by the IR and must be purchased from the OEM, who sells them at a markup. To become a competitive lever, the OEM chooses such parts to be proprietary, which show a high failure rate (compare the quote from Independent remanufacturer B in the introduction). In order to focus on the OEM's spare parts decision, we assume the failure rate to be one. Thus, the IR can not scavenge collected cores for those parts. There is no such restriction for non-proprietary parts that are procured from the market.

OEM decision and cost. The OEM decides to introduce proprietary parts. Redesigning parts causes fixed design cost F per period and, proportional to the proprietary content, it increases the marginal cost of both, producing new products as well as proprietary spare parts. Thus, the OEM will typically try to make small, inexpensive parts proprietary to keep his additional cost low, but still exert control over the profitability of the secondary market. An extreme example of this is the software re-licensing issue analyzed in Oraiopoulos et al. (2012), as arguably the variable cost of software is zero. Also, the quote from independent remanufacturer B, mentioned in the introduction, indicates that OEMs choose low-cost electronics parts as candidates for being proprietary. Based on these observations, we let the parameter β reflect the fraction of the product that is proprietary, and assume that β is an industry-specific parameter, representing the smallest possible part that can be redesigned appropriately.

Given β, unit production cost, c_n, are

$$c_n = \beta(1+\psi)c + (1-\beta)c = (1+\beta\psi)c, \tag{1}$$

where c is the unit cost of a completely non-proprietary product, and ψ is the percentage cost increase of a fully proprietary product. Analogously, unit production cost of proprietary spare parts, c_p, is

$$c_p = \beta(1+\psi)c. \tag{2}$$

IR decision and cost. The OEM sets a per-unit wholesale price $w_s \geq c_p$ he charges the IR for the proprietary fraction β of the product provided as a spare part. For the remaining portion of the product $1-\beta$, we assume that there is a cost advantage of remanufacturing over new production, $0<\phi<1$. Consequently, the unit remanufacturing cost for the IR, c_r, become

$$c_r = w_s + (1-\beta)\phi c, \tag{3}$$

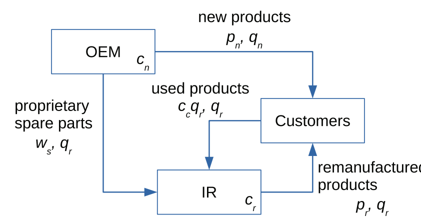

Fig. 1. Model structure with proprietary parts.

Table 1
Summary of model notation.

Parameters:	
$0<\beta\leq 1$	Fraction of the product that is proprietary (proprietary content)
$0<c<1$	Marginal cost of a new product without proprietary content ($\beta=0$)
$0\leq\psi$	Marginal cost increase induced by a fully proprietary product ($\beta=1$)
$0<\phi<1$	Cost advantage due to remanufacturing
$0<c_c$	Collection cost coefficient
$0<\delta<1$	WTP discount factor for remanufactured products
$0<\gamma\leq 1$	Core collection yield factor, defined as the fraction of used products that is collectable
$0<F$	cost for designing proprietary content
Decision variables:	
w_s	Wholesale price of (proprietary content) spare parts (OEM)
p_n	Sales price of new products (OEM)
p_r	Sales price of remanufactured products (IR)
Auxiliary variables:	
q_n	Sales quantity of new products
q_r	Sales quantity of remanufactured products
$\tilde{c}$	Effective remanufacturing cost

being larger than the *effective remanufacturing cost* (without a markup), $\tilde{c}$, which would be

$$\tilde{c} = \beta(1+\psi)c + (1-\beta)\phi c. \tag{4}$$

In line with Atasu et al. (2013), the IR faces convex collection cost $c_c q_r^2$ for the used products, where q_r is the collection quantity and $c_c \geq 0$ is a scaling parameter. Note that the IR would never collect more than she wishes to remanufacture. Thus, q_r is also the number of remanufactured units offered to the secondary market at a price of p_r.

Consumer behavior. To finalize the description of our model, we need to characterize how the prices for new and remanufactured products, p_n and p_r, respectively, will shape the demands on the primary and secondary market. Here we follow the utility based approach (Abbey et al., 2017; Debo et al., 2005; Oraiopoulos et al., 2012; Souza, 2013, see, e.g.,), which assumes that the willingness-to-pay for the new product is distributed uniformly in the interval [0,1], and that all consumers show a lower willingness-to-pay for the remanufactured product, reflected by a commonly applied discount factor $\delta<1$. Normalizing the market size to one, this yields linear demand functions as follows (Abbey et al., 2017):

$$q_n(p_n,p_r) = 1 - \frac{p_n-p_r}{1-\delta} \quad \text{and} \quad q_r(p_n,p_r) = \frac{\delta p_n - p_r}{\delta(1-\delta)} \tag{5}$$

Fig. 1 visualizes the basic structure of our model. For ease of reference, Table 1 summarizes our notation. In the considered Stackelberg setting with the OEM as a leader, the timeline of the decisions is given by the following steps:[6]

[6] To test the robustness of our results with respect to the competitive setting, we also considered two alternative model variants. The first one keeps the Stackelberg structure and replaces the market price competition with quantity competition, i.e.,

Table 2
Equilibrium prices and quantities with generic parts.

Strategy region	No remanufacturing	Partial remanufacturing	Full remanufacturing
p_n	$\frac{1+c}{2} - \frac{\delta^2(1-c)}{8c_c+8\delta-6\delta^2}$	$\frac{1+c}{2} - \frac{\delta(\delta-c\phi)}{4c_c+4\delta-2\delta^2}$	$\frac{1+c}{2} - \frac{\delta(\delta+\gamma(\delta(2-\delta)+2c_c))(1-c)}{8c_c+8\delta-6\delta^2+\gamma\delta(4c_c+4\delta-2\delta^2)}$
p_r	n.a.	$\delta\,\frac{1+c}{2} - \frac{\delta(\delta-c\phi)}{4c_c+4\delta-2\delta^2} - \frac{\delta(1-\delta)(\delta-\phi)c}{4c_c+4\delta-4\delta^2}$	$\delta p_n - \frac{2\delta(1-\delta)\gamma(\delta(2-\delta)+2c_c)(1-c)}{8c_c+8\delta-6\delta^2+\gamma\delta(4c_c+4\delta-2\delta^2)}$
q_n	$\frac{1-c}{2} + \frac{\delta^2(1-c)}{8c_c+8\delta-6\delta^2}$	$\frac{1-c}{2} - \frac{\delta(\delta-\phi)c}{4c_c+4\delta-4\delta^2}$	$\frac{1-c}{2} + \frac{\delta(\delta-\gamma(\delta(2-\delta)+2c_c))(1-c)}{8c_c+8\delta-6\delta^2+\gamma\delta(4c_c+4\delta-2\delta^2)}$
q_r	0	$\frac{\delta-c\phi}{4c_c+4\delta-2\delta^2} + \frac{(\delta-\phi)c}{4c_c+4\delta-4\delta^2}$	γq_n

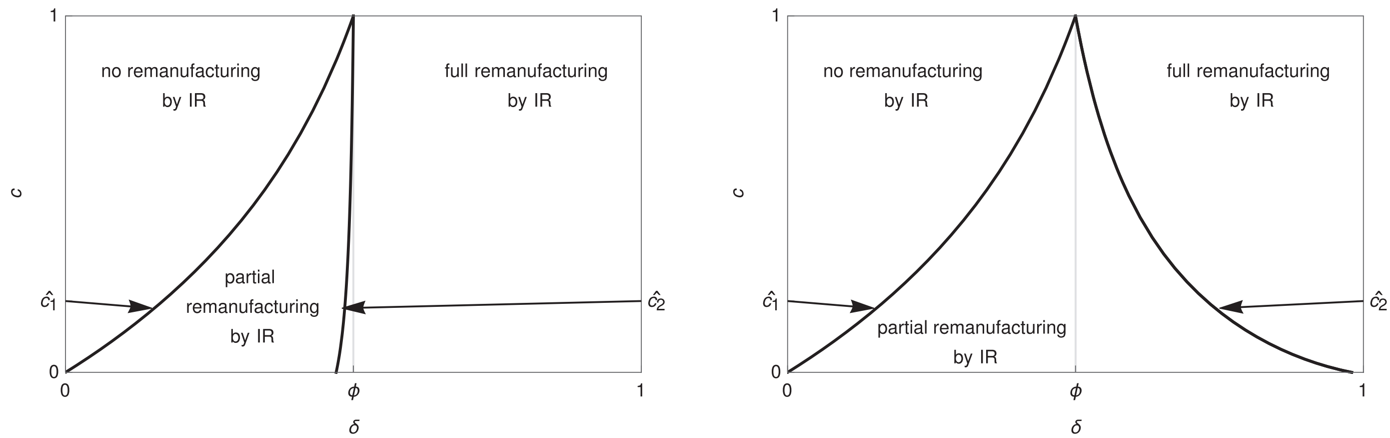

Fig. 2. Characterization of the strategy regions when the OEM does not use proprietary parts for $\gamma < \hat{\gamma}$ (left) and $\gamma \geq \hat{\gamma}$ (right). Parameters values are $\phi = 0.5$, $\psi = 1$, $c_c = 0.2$, $\beta = 0.1$, and $\gamma = 0.42$ (left) or $\gamma = 0.7$ (right).

1. Initially, the OEM decides whether or not to introduce proprietary parts to his product.
2. Then the OEM decides on the price for the new product p_n and, if applicable, on the wholesale price for proprietary spare parts w_s.
3. Finally, the IR decides on the price of remanufactured products p_r.

The equilibrium to all considered model variants is derived through backward induction. Thus, below we first present the optimal decisions of the OEM and the IR under a fixed proprietariness setting.

3.2. Benchmark: selling the product with generic parts

When the OEM refrains from introducing proprietary parts, the production cost is $c_n = c$ and manufacturing cost becomes $c_r = \phi c$ due to the fully generic content of the product. The profit functions of the OEM and the IR in the considered Stackelberg game with the OEM as the leader are as follows.

$$\max_{p_n} \Pi^{OEM}_{gen}(p_n|p_r) = (p_n - c)q_n \quad \text{s.t.} \quad 0 \leq q_n \tag{6}$$

$$\max_{p_r} \Pi^{IR}_{gen}(p_r|p_n) = (p_r - \phi c - c_c q_r)q_r \quad \text{s.t.} \quad 0 \leq q_r \leq \gamma q_n \tag{7}$$

Besides non-negativity constraints on all quantities, the IR faces the core availability constraint $q_r \leq \gamma q_n$.

The following lemma characterizes the different equilibrium strategy regions when selling the product with generic parts (For all proofs see Appendix A).

the OEM sets q_n while the IR sets q_r. The second one assumes that market prices are determined simultaneously by the OEM and the IR. We model this as a Nash-game. It turns out that the main structural insights are unchanged. The results are provided in Appendix C.

Lemma 1. *In the case of generic parts, characteristics of the equilibrium regions are provided in Table 2. There exists a threshold value for the core collection yield factor, $\hat{\gamma}$, and two threshold values for the marginal cost of a new product $\hat{c}_1$ and $\hat{c}_2$ (for functional forms see the proof in Appendix A). The equilibrium regions can be described as follows:*

No remanufacturing. If $\delta \leq \phi$ and $c \geq \hat{c}_1$, the IR does not enter the market, i.e., $q_r = 0$.

Partial remanufacturing. If ($\delta \leq \phi$ and $\hat{c}_1 > c > \hat{c}_2$) OR ($\delta > \phi$ and $\gamma \geq \hat{\gamma}$ and $c < \hat{c}_2$), the IR enters the market but does not remanufacture all available cores, i.e., $0 < q_r < \gamma q_n$.

Full remanufacturing. If ($\delta \leq \phi$ and $\hat{c}_2 \geq c$) OR ($\delta > \phi$ and $\gamma \geq \hat{\gamma}$ and $c \geq \hat{c}_2$) OR ($\delta > \phi$ and $\gamma < \hat{\gamma}$), the IR enters the market and remanufactures all available cores, i.e., $q_r = \gamma q_n$.

Fig. 2 visualizes the strategy space for the two cases regarding whether the core collection yield factor, γ, is larger or smaller than threshold $\hat{\gamma}$. In case of pure price competition, the OEM reacts to the entry threat – even if the IR does not enter the market – by reducing the price of new products (Atasu et al., 2008, compared with a monopoly market price $p_n = \frac{1+c}{2}$, see,) and giving up some profit. If consumers put a low value on the remanufactured version of a low margin product (δ small and c high), the OEM thus deters market entry by the IR and avoids cannibalization of new product demand.

3.3. Selling the product with proprietary parts

In this section, we study how the use of proprietary parts affects the competitive environment. The competitive pricing solution is obtained from the following price game between the manufacturer and the IR:

$$\max_{p_n, w_s} \Pi^{OEM}_{prop}(p_n, w_s|p_r) = (p_n - c_n)q_n + (w_s - c_p)q_r - F \quad \text{s.t.} \quad 0 \leq q_n \tag{8}$$

Table 3
Equilibrium prices and quantities in all three strategy regions.

Strategy region	No remanufacturing	Partial remanufacturing	Full remanufacturing
w_s	$\geq c_p + \frac{\delta(1-c_n)}{2}$	$c_p + \frac{\delta-\tilde{c}}{2}$	$c_p + \frac{(\delta+2c_c\gamma+(2-\delta)\delta\gamma)(1-c_n)}{2(1+\delta\gamma)}$
p_n	$\frac{1+c_n}{2}$	$\frac{1+c_n}{2}$	$\frac{1+c_n}{2}$
p_r	n.a.	$\delta p_n - \frac{\delta(1-\delta)(\delta c_n-\tilde{c})}{4(c_c+\delta(1-\delta))}$	$\delta p_n - \frac{\gamma\delta(1-\delta)(1-c_n)}{2(1+\delta\gamma)}$
q_n	$\frac{1-c_n}{2}$	$\frac{1-c_n}{2} - \frac{\delta(\delta c_n-\tilde{c})}{4(c_c+\delta(1-\delta))}$	$\frac{1-c_n}{2} - \frac{\gamma\delta(1-c_n)}{2(1+\delta\gamma)}$
q_r	0	$\frac{\delta c_n-\tilde{c}}{4(c_c+\delta(1-\delta))}$	γq_n

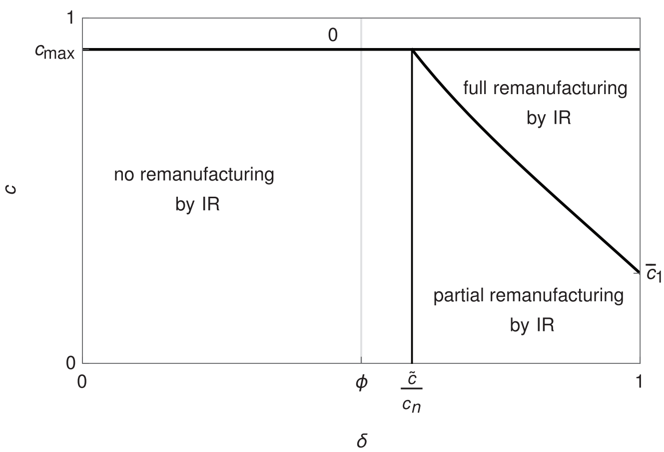

Fig. 3. Characterization of the strategy regions in the case of an OEM using proprietary parts. ($\phi = 0.5$, $\psi = 1$, $c_c = 0.2$, $\beta = 0.1$, and $\gamma = 0.7$).

$$\max_{p_r} \Pi^{IR}_{prop}(p_r|p_n, w_s) = (p_r - c_r - c_c q_r)q_r \quad \text{s.t.} \quad 0 \leq q_r \leq \gamma q_n \tag{9}$$

Note that by model design the unit production cost of a new product must not exceed an upper bound, $c_{\max}$, which corresponds to the fraction of proprietary content β, i.e., $c < c_{\max} = \frac{1}{1+\beta\psi}$. Otherwise, new production would become non-profitable.

The following lemma characterizes the different strategy regions in the equilibrium.

Lemma 2. *In the case of proprietary parts, characteristics of the equilibrium regions are given in Table 3. If new production is profitable ($c < c_{\max}$), there exists a threshold value for the marginal production cost of a new product, $\bar{c}_1$ (for functional form see the proof in Appendix A), and the equilibrium regions can be described as follows:*
No remanufacturing. If $\delta < \frac{\tilde{c}}{c_n}$, the IR does not enter the market and the OEM acts like a monopolist, i.e., $q_r = 0$.
Partial remanufacturing. If $\delta \geq \frac{\tilde{c}}{c_n}$ and $c < \bar{c}_1$, the IR enters the market but does not remanufacture all available cores, i.e., $0 < q_r < \gamma q_n$.
Full remanufacturing. If $\delta \geq \frac{\tilde{c}}{c_n}$ and $c \geq \bar{c}_1$, the IR enters the market and remanfactures all available cores, i.e., $q_r = \gamma q_n$.

Fig. 3 shows the strategy space. Note that region 0 depicts the disregarded case where new production is not viable.

Using the results from Lemma 2, we can characterize the effect of β on the IR entry deterrence by the OEM.

Proposition 1. *It is optimal for the OEM to deter market entry by the IR – by setting the spare parts price w_s accordingly – whenever $\beta > \frac{\delta-\phi}{1-\phi+(1-\delta)\psi}$.*

Proposition 1 complements the results from Oraiopoulos et al. (2012) for the case of relicensing fees – which arguably coincide with zero proprietariness of the product itself – where it was found that the OEM only deters entry by the IR if the secondary market is not very profitable, e.g., shown in a low customer valuation δ. This of course also holds in our model, where Fig. 3 shows that for small values of δ entry deterrence is optimal. In our case, however, even a large δ – implying that the secondary market is very profitable – does not ensure market entry of the IR as long as β is large enough. If the resulting additional cost of providing spare parts, also impacted by ψ, is high, the OEM prefers to price the parts such high to makes it no longer worthwhile for the IR to enter the secondary market.

On the other hand, we find that for sufficiently high δ and small β, it is indeed optimal for the OEM to let the IR enter. Under optimal choice of the wholesale price w_s (as shown in Table 3), the OEM's extra profits due to spare parts sales compensate for the reduced profits on the primary market caused by the cannibalization of new product sales in such a scenario.

3.4. Comparison of strategies under the use of proprietary parts versus generic parts only

Having analyzed the strategies under generic parts only and proprietary parts, respectively, we now turn to a comparison of the two strategies. Comparing Table 3 with Table 2 reveals another interesting result. Without proprietary parts, the OEM lowers its price p_n – taking the market conditions into account – to establish a more hostile environment for the IR. Conversely, when introducing proprietary parts, the OEM controls competition solely through the choice of the wholesale price w_s for spare parts, without the need to adapt the market price for new products p_n. Moreover, we also find that under proprietary parts, the OEM can deter entry by the IR for a wider range of cost values c and WTP discount factor values δ. In other words, when using proprietary parts, the OEM may find it optimal to deter entry, when it would otherwise – when using generic parts only – be faced with partial or full remanufacturing by the IR.

Further, an analysis of the boundaries separating the partial and full remanufacturing responses of the IR in settings with and without proprietary parts ($\bar{c}_1$ and $\hat{c}_2$, respectively) shows two interesting facts. When γ is low, i.e., the core collection yield is low, or γ is high, but $c_c = 0$, i.e., collection is free we find that $\hat{c}_2 < \bar{c}_1$ always holds, and, more generally, the use of proprietary parts always reduces the level of remanufacturing. In those scenarios, the OEM uses the proprietary parts to protect its primary market profits. However, when γ is high, and c_c is sufficiently large as well, the OEM may find it optimal – by setting the spare parts price w_s accordingly – to induce the IR to remanufacture fully under proprietary parts, when the IR would only partially remanufacture if all parts were generic, i.e., we get $\hat{c}_2 > \bar{c}_1$. This reflects once again the overall profit view of the OEM, who may find it optimal to accept lower primary market profits in exchange for an increase in secondary market profits due to spare parts sales.

Now that we have discussed the different market implications of using versus not-using proprietary parts, we can finally focus on the OEM's decision whether or not to introduce proprietary parts at all. To do so, we need to compare the profits under the two strategies. Since the OEM will prefer introducing proprietary parts unless the cost of doing so is too high, an increase in β, ψ, or F makes the introduction of proprietary parts less favorable. However, for the remaining parameters, no such clear-cut results hold in general. Thus, below we will resort to numerical analysis to provide insights into the impact of each parameter on the decision and profitability of using proprietary parts.

Before we do that, we turn to one interesting particular scenario. From Lemma 1 and Fig. 2 we know that when the OEM uses only generic parts, the IR does not enter the secondary market for small WTP discount factor, $\delta \leq \phi$, and high new product's

Table 4
Experimental design.

Parameter	β	c	ψ	ϕ	c_c	δ	γ	ξ	ν
Low	0.1	0.2	0	0.3	0.1	0.5	0.3	0.0001	0
High	0.3	0.6	0.25	0.7	0.3	0.85	0.7	0.001	2

unit cost, $c \geq \hat{c}_1$. In that case, it would seem that introducing proprietary parts cannot make sense. However, Proposition 2 provides conditions under which the OEM is better off by introducing proprietary parts.

Proposition 2. *Assume that $\delta \leq \phi$, and $c \geq \hat{c}_1$, i.e., the IR would not enter even if the OEM only uses generic parts. In that case, the OEM still prefers to introduce proprietary parts when*

$$0 < \beta < \frac{1 - c - 2\sqrt{\frac{2(1-c)^2(2c_c+(2-\delta)\delta)(c_c+\delta-\delta^2)}{(4c_c+(4-3\delta)\delta)^2}} + F}{c\psi} \tag{10}$$

For such a situation to exist, the right-hand side term in inequality (10) must be positive, requiring, e.g., the cost for designing proprietary content, F, not to be too large. Thus, the OEM benefits from introducing proprietary parts and pricing them prohibitively expensive in order not to sell them to the IR. Thereby the OEM avoids the profit loss due to the strategic price reduction for the new product p_n. The condition given in Proposition 2 provides an upper bound on the fraction of proprietary content β that guarantees that the associated extra primary market profit outweighs the cost of introducing proprietariness.

To explicitly quantify the economic differences between using and not using proprietary parts by the OEM, we now present the results of a comprehensive numerical analysis. After introducing the experimental design, we focus on the OEM's profitability and decision making but also briefly highlight the implications for the IR and the consumers.

3.4.1. Experimental design

To capture a wide set of industry scenarios, we employ a full-factorial experimental design. For each relevant parameter, we consider two values, a high one and a low one. These values are shown in Table 4 and were chosen in line with previous work on remanufacturing (Ferguson, Fleischmann, & Souza, 2011; Ferguson, Guide, & Souza, 2006; Guide, Souza, Van Wassenhove, & Blackburn, 2006; Subramanian & Subramanyam, 2012). The values of β and ψ were estimated based on interviews with company representatives from both computer OEMs as well as white-goods OEMs. In terms of fixed design cost F, we utilize the possibilities of the numerical study to analyze different structures. Specifically, we define $F = \xi\beta^{\nu}$, where ξ reflects the design cost factor for making proprietary content and ν models the design efficiency. For ν, we consider two special but realistic cases. The first one ($\nu = 0$) reflects a fixed design cost, which is independent of the fraction of proprietary content in the final product. The second one ($\nu = 2$) represents quadratic cost, which models the increasing difficulty of making a larger proportion of the product proprietary. Finally, the values of ξ have been chosen such that all strategy regions are relevant. Overall, we obtain 512 instances (9 parameters with 2 realizations each, i.e. $2^9 = 512$). The full set of results can be obtained from the authors. Here, for the sake of brevity, we focus on the most relevant, aggregated results.

3.4.2. Profit and decision-making impact on the OEM

We first consider the profit impact of using proprietary parts on the OEM. On average over all the 512 instances, the OEM gains 55% (computed as $\frac{\Pi^{OEM}_{prop} - \Pi^{OEM}_{gen}}{\Pi^{OEM}_{gen}}$) by using proprietary parts. The violin plot in Fig. 4 presents the distribution of percentage changes in OEM profit when introducing proprietary parts, supporting the widespread use of proprietary parts in practice.

To get a deeper insight, we take a more granular look at our results. Specifically, for each model, we distinguish between the cases with ($q_r > 0$) and without ($q_r = 0$) remanufacturing. Tables 5 and 6 provide the results for each of the resulting four strategy combinations. The left panel of Table 5, showing the prevalence of each combination, confirms that we can never have a situation where there is remanufacturing under the use of proprietary parts but no remanufacturing without proprietary parts. In 25% of the cases, the OEM deters entry by the IR through using proprietary parts when in the case of generic parts, he would let the IR enter. However, in the majority of cases, it is optimal not to deter IR market entry regardless of whether or not proprietary parts are used.

The right panel of Table 5 provides the profit implications of using proprietary parts (compared to not using them) for these different strategy combinations. Clearly, profit differences are more pronounced when it is optimal for the OEM, who introduces proprietary parts, to let the IR enter the secondary market. Here, the OEM capitalizes on profitably selling proprietary parts and thereby sharing the revenues on the secondary market with the IR. This is also shown by the results in Table 6, where we present the average price and quantity changes on both the primary and the secondary market (where applicable). Clearly, in the scenarios where the IR enters regardless of the OEM's strategy, the introduction of proprietary parts allows the OEM to charge a 30% higher price for new products while only facing a 19% reduction in quantities. Thus, the OEM does not only benefit from the secondary market but also enjoys increased primary market profits.

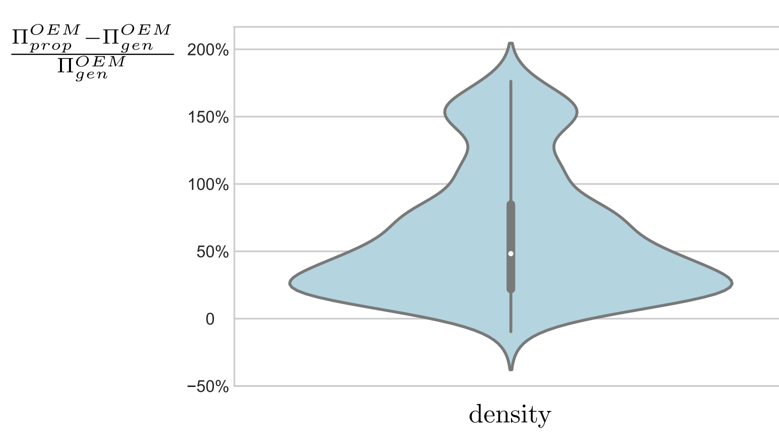

Fig. 4. Violin plot of relative OEM profit changes.

Table 5
Distribution of instances (left panel) and average relative OEM profit changes (right panel).

# of instances		Model *gen*		$\frac{\Pi^{OEM}_{prop}-\Pi^{OEM}_{gen}}{\Pi^{OEM}_{gen}}$		Model *gen*	
		No reman	Reman			No reman	Reman
Model *prop*	No reman	64	128	Model	No reman	−6%	21%
prop	Reman	0	320	*prop*	Reman	–	81%

Table 6
Average relative price changes (left panel) and quantity changes (right panel).

$\frac{p_{n,prop}-p_{n,gen}}{p_{n,gen}}$		Model *gen*		$\frac{q_{n,prop}-q_{n,gen}}{q_{n,gen}}$		Model *gen*	
$\left(\frac{p_{r,prop}-p_{r,gen}}{p_{r,gen}}\right)$		No reman	Reman	$\left(\frac{q_{r,prop}-q_{r,gen}}{q_{r,gen}}\right)$		No reman	Reman
Model	no reman	4% (–)	14% (–)	Model	no reman	−15% (–)	−4% (−100%)
prop	reman	– (–)	30% (37%)	*prop*	reman	– (–)	−19% (−64%)

Table 7
Impact of model parameters on average relative OEM profit changes.

$\frac{\Pi^{OEM}_{prop}-\Pi^{OEM}_{gen}}{\Pi^{OEM}_{gen}}$				c							
				low				high			
				ϕ				ϕ			
				low		high		low		high	
				c_c		c_c		c_c		c_c	
				low	high	low	high	low	high	low	high
δ	low	γ	low	19%	17%	19%	16%	14%	11%	−6%	−7%
			high	44%	27%	25%	16%	40%	35%	−6%	−7%
	high	γ	low	75%	49%	72%	47%	65%	44%	64%	41%
			high	**156%**	110%	**151%**	96%	**155%**	126%	**145%**	99%

We also observe that, on average, the OEM is worse off by introducing proprietary parts to deter the IR in an environment in which this would occur under generic parts as well. In those cases, the average profit change is −6%, as shown in the right panel of Table 5. This decrease results from situations in which we find a high fixed cost, F, or a large proprietary content, β. Disaggregating the results, however, reveals that there are 24 instances in line with Proposition 2, in which the OEM prefers to introduce proprietary parts with an average profit increase of 1.6%. Summarizing, our results suggest that using proprietary parts to preempt the secondary market is the preferred option for the OEM only in a minority of possible environments. In most of the considered scenarios, the OEM benefits more from strategically using these proprietary parts to skim some profits from the secondary market.

To conclude this part of our analysis we show the impact of the model parameters on the relative OEM profit changes. The effects of β, ψ and F have been discussed before, so in the presentation in Table 7, we focus on the remaining five parameters. In terms of individual parameters, we find that increases in δ and γ enhance the OEM's relative profitability of introducing proprietary parts, while increases in c, c_c, and ϕ reduce the benefits of introducing proprietary parts. Quantitatively, we observe that δ has the strongest effect, while the impact of c and ϕ is mild to negligible.

Overall, using proprietary parts is particularly beneficial for the OEM when γ and δ are high, while c_c is low. In such an environment (bold numbers in Table 7), the average profit increase from proprietary parts is around 150%. In other words, when cores are freely available as well as cheap to collect, and consumers have a high acceptance of remanufactured products, the OEM would forego substantial benefits by not using proprietary parts and sharing the secondary market profits with the IR. On the other hand, the combination of high values of c, ϕ, and c_c with a small δ constitutes the most hostile environment for proprietary parts. Here, the primary market is small and little profitable. Moreover, remanufactured products can only be sold at a significant discount and are both costly to collect and remanufacture. Jointly, these market characteristics (underlined numbers in Table 7) make the investment in proprietary parts costly (in terms of primary market profits) but little effective (in terms of gains from preempting the secondary market). Specifically, the OEMs profit would decrease by an average of 6–7% when using proprietary parts, implying that the OEM should stick with a purely generic product.

Table 8
Average relative IR profit changes and consumer surplus changes (in brackets).

$\frac{\Pi^{IR}_{prop}-\Pi^{IR}_{gen}}{\Pi^{IR}_{gen}}$ $\left(\frac{\Upsilon_{prop}-\Upsilon_{gen}}{\Upsilon_{gen}}\right)$		Model *gen*	
		No reman	Reman
Model *prop*	No reman	– (−27%)	−100% (−36%)
	Reman	–	−93% (−54%)

3.4.3. Impact on the IR and consumer surplus

To conclude this section, we briefly highlight and discuss the effect of the strategy adopted by the OEM on the IR's profit as well as on consumer surplus. In line with the assumptions made for deriving demand functions (5), we define the consumer surplus Υ to be the cumulative difference between a consumer's willingness to pay for the chosen product (new or remanufactured) and the corresponding price, which calculates as follows (for a derivation see Appendix B)

$$\Upsilon = q_n\left(1 - p_n - \frac{q_n}{2}\right) + \frac{\delta q_r^2}{2} \tag{11}$$

Table 8 shows the average relative changes in IR profits and consumer surplus (in brackets). As expected, both IR and consumers are worse off when the OEM introduces proprietary parts. Interestingly, the OEM can essentially extract all the extra profits from the secondary market when introducing proprietary parts and letting the IR enter. Also, consumer surplus takes the most sub-

Table 9
Equilibrium prices and quantities under OEM remanufacturing in all three strategy regions.

Strategy region	No remanufacturing	Partial remanufacturing	Full remanufacturing
p_n	$\frac{1+c_n}{2}$	$\frac{1+c_n}{2}$	$\frac{1+c_n}{2} - \frac{\gamma(\delta c_n - \tilde{c}(1+\gamma\delta)+\gamma(\alpha c_c+\delta)c_n - \gamma(\alpha c_c+\delta(1-\delta)))}{2(1+2\delta\gamma+(\alpha c_c+\delta)\gamma^2)}$
p_r	n.a.	$\delta p_n - \frac{\delta(1-\delta)(\delta c_n-\tilde{c})}{2(\alpha c_c+\delta(1-\delta))}$	$\delta p_n - \frac{\delta(1-\delta)\gamma(1-c_n+\gamma(\delta-\tilde{c}))}{2(1+2\delta\gamma+(\alpha c_c+\delta)\gamma^2)}$
q_n	$\frac{1-c_n}{2}$	$\frac{1-c_n}{2} - \frac{\delta(\delta c_n-\tilde{c})}{2(\alpha c_c+\delta(1-\delta))}$	$\frac{1-c_n+\gamma(\delta-\tilde{c})}{2(1+2\delta\gamma+(\alpha c_c+\delta)\gamma^2)}$
q_r	0	$\frac{\delta c_n-\tilde{c}}{2(\alpha c_c+\delta(1-\delta))}$	γq_n

stantial dip in those cases. The reason for this is the large price increase on both the primary and secondary markets and the associated massive drop in remanufactured product sales (compare Table 6).

4. Remanufacturing by the OEM

So far, we considered the case of a non-remanufacturing OEM. As mentioned in Section 3.1, the reasons for not remanufacturing come from two categories, namely, demand-based and resource-based issues. On the demand side, the cannibalization of new product sales critically impacts the OEM's decision not to sell remanufactured products. However, this opens the door for IRs who do not worry about primary market profits. In the above analysis, we have seen how the non-remanufacturing OEM combines proprietary parts and an appropriate pricing strategy to counter the entry threat by an IR. Yet, there may still be resource-based obstacles, including the lack of remanufacturing capabilities as well as the difficulty of accessing cores. While the former hurdle is internal to the OEM, the latter relates to competition with the more locally operating IR who may collect cores more efficiently. In this case, the OEM may be reluctant to develop its internal remanufacturing skills. However, if the OEM could more easily access the cores, he might consider remanufacturing more favorably. In solving this issue, proprietary parts can play a role since pricing these parts to deter market entry also removes the IRs incentive to collect cores. Thus, the OEM may gain exclusive access to used products and might decide to perform remanufacturing himself. In what follows, we analyze this scenario by assuming that the OEM sets the wholesale price of the proprietary content, w_s, such high that the IR is deterred.

For parsimony (w.l.o.g.), we consider the same demand functions (5) as in the IR remanufacturing case by assuming that the valuation of the products does not depend on whether the OEM or the IR remanufactures. Keeping the basic cost structure from the case of a non-remanufacturing OEM (see Section 3.3), the OEM's cost for remanufacturing a product with β proprietary content is given by

$$c_r^{OEM} = c_p + (1-\beta)\phi c. \tag{12}$$

Since OEMs typically are large multinational companies, having to collect from long distances, and IRs are (relatively) small local firms, we assume that the OEM faces higher collection effort. This is modeled using a factor $\alpha > 1$ on the collection cost which represents the collection cost disadvantage. Under these conditions, the OEM's objective function becomes

$$\Pi_{prop+rem}^{OEM}(p_n, p_r) = (p_n - c_n)q_n + (p_r - c_r^{OEM} - \alpha c_c q_r)q_r - F. \tag{13}$$

Again, the core availability constraint $q_r \leq \gamma q_n$ has to hold. Lemma 3 characterizes the strategy applied by the OEM.

Lemma 3. *In the case of proprietary parts, characteristics of the equilibrium regions under OEM remanufacturing are given in Table 9. If new production is profitable ($c < c_{\max}$), there exists a threshold value for the marginal production cost of a new product, $\bar{c}_3$ (for functional form see the proof in Appendix A), and the equilibrium regions can be described as follows:*

No remanufacturing. If $\delta < \frac{\tilde{c}}{c_n}$, the OEM does not remanufacture, i.e., $q_r = 0$.

Partial remanufacturing. If $\delta \geq \frac{\tilde{c}}{c_n}$ and $c < \bar{c}_3$, the OEM remanufactures some cores, i.e., $0 < q_r < \gamma q_n$.

Full remanufacturing. If $\delta \geq \frac{\tilde{c}}{c_n}$ and $c \geq \bar{c}_3$, the OEM remanufactures all available cores, i.e., $q_r = \gamma q_n$.

Note that the only structural difference between the equilibrium regions under OEM remanufacturing as shown in Lemma 3 and the ones under IR remanufacturing shown in Lemma 2 is the threshold value for the marginal production cost of a new product, $\bar{c}_3$. This difference is characterized in the following lemma.

Lemma 4. *Whenever $1 \leq \alpha \leq 2 + \frac{\delta(1-\delta)}{c_c}$ we observe that $\bar{c}_1 \geq \bar{c}_3$. Conversely, whenever $\alpha > 2 + \frac{\delta(1-\delta)}{c_c}$ we get $\bar{c}_1 < \bar{c}_3$.*

This implies that for small α, i.e., when the OEMs collection disadvantage is not too pronounced, the OEM will switch from partial to full remanufacturing at smaller production cost c than the IR. Comparing the remanufacturing quantities in Tables 3 with their respective counterparts in Table 9, we obtain the following result:

Proposition 3. *In cases where remanufacturing takes place, i.e. $\delta \geq \frac{\tilde{c}}{c_n}$, and where the collection cost disadvantage of the OEM is not too severe, i.e., $\alpha \leq 2 + \frac{\delta(1-\delta)}{c_c}$, the OEM always remanufactures more than the IR would. Even if $\alpha > 2 + \frac{\delta(1-\delta)}{c_c}$, the OEM remanufactures more than the IR would whenever $c > \bar{c}_3$.*

Note that this result is counter to the extant finding in the literature (see, e.g. Ferguson & Toktay, 2006), according to which the OEM has less inclination to remanufacture than an IR, since he takes into account not only the potential extra profit on the secondary market but also the profit decline in the primary market. Our result is driven by a missing double marginalization effect from selling spare parts, i.e., the OEM takes full advantage of any spare part used and thus sells more remanufactured units.

Using the same experimental setup as in the previous section, we have quantified the increase in the remanufacturing quantity q_r as well as the change in OEM profit when switching from IR to OEM remanufacturing. Regarding the collection cost disadvantage of the OEM, we assume two scenarios, namely $\alpha = 2$ and $\alpha = 5$ corresponding to low and high collection cost disadvantage of the OEM as characterized in Lemma 4, respectively.

For $\alpha = 2$, we observe that the OEM on average receives an extra profit of more than 6%. Additionally, on average, the OEM remanufactures around 24% more units than the IR would. For $\alpha = 5$ and in line with Proposition 3, OEM remanufacturing exceeds IR remanufacturing only if $c > \bar{c}_3$. This scenario occurs in 20% of the relevant cases, and the average increase in OEM profit and the remanufacturing quantity is 21% and 8%, respectively.

As the OEM remanufacturing removes the double marginalization effect arising when the IR would remanufacture using parts bought from the OEM, this also increases consumer surplus by roughly 8% on average. However, these benefits do not outweigh the losses faced by the consumers after the introduction of proprietary parts (compare Table 8). Overall, in the described cases, the

OEM benefits from using proprietary spare parts (and remanufacturing himself), while both the IR and the consumers lose.

5. Conclusions

In this paper, we examine the competition between an OEM and an IR, where the OEM strategically adopts proprietary parts as a means to obtain a competitive edge over IRs, and exert greater control over the secondary market of remanufactured products. This study was inspired by various first-hand accounts, as well as cases reported in the media of such a strategy.

We contribute to the existing literature by developing a framework for strategic decision making concerning pricing (i.e., pricing of new and remanufactured products) and the use of proprietary parts. This enables the OEM to sufficiently control the secondary market while keeping design and (re-)manufacturing cost low. Moreover, by appropriately pricing the proprietary parts, governance of the secondary market is possible for the OEM without reducing the price of new products. Complementing the results from Oraiopoulos et al. (2012) for the case of relicensing fees, the use of proprietary parts to starve the secondary market is a suitable strategy for the OEM not only when the willingness-to-pay for remanufactured products is low but also if the cost of providing such spare parts is high. This helps in explaining the apparent prevalence of such a strategy in the white-goods industry, particularly for washing machines, as indicated by our accounts with IRs in that industry.

Further, we find that the OEM might benefit from easier access to cores. Global OEMs may find it difficult to compete with local IRs in collecting cores. Here, the use of proprietary parts and a prohibitive pricing strategy not only deters remanufacturing by the IR but also discourages collection of cores, giving the OEM a first-mover advantage (see, e.g., Ferguson & Toktay, 2006). This effect can lead to situations where the OEM could remanufacture more items than the IR would. While this result depends on the relative collection cost of the OEM compared to the IR, we find that even under a twofold increase in the collection cost, the OEM can extract a significant extra profit with this strategy.

The insights of this paper are also relevant to IRs and policy-makers. We demonstrated that even small changes in product design in the direction of making it more proprietary can lead to the collapse of the secondary market, and have severe consequences to IRs and consumers. We observed that IRs might even be pushed out of the secondary market completely. Moreover, consumer surplus also decreases when proprietary parts are adopted. Yet, OEM remanufacturing softens this loss, at least for consumers. Thus, any initiatives targeting standardization should be scrutinized by policy-makers to ensure an overall benefit to the various stakeholders.

For future research, we encourage the examination of the scenario where cores can be scavenged for parts by the IR. Since parts scavenged from other cores by the IR reduce the volume of spare parts the OEM can sell, it would be interesting to study the OEMs durability/quality decision of his (proprietary) parts under such a threat.

Finally, we have assumed that the OEM is a monopolist on the primary market. While this is a reasonable proxy to model particular market niches, there are many situations where competition with other OEMs will decidedly shape an OEM's decision. Regarding the optimal proprietary content in the new product, such a case could arise when the IR can remanufacture cores from different OEMs. In such a context, OEMs may even consider exclusivity clauses, where an IR is authorized to remanufacture the OEM's cores only if it does not remanufacture any other OEM's cores. A more detailed treatment of the effect of these complicating factors on the OEM's profitability presents another promising avenue for further research that can provide additional insights into the optimal proprietariness decisions by the OEM.

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Appendix A. Proofs

Proof of Lemma 1

We omit details of the proof here since it follows along the same lines as the proof for our main model in Lemma 2 given below. Yet, the detailed exposition of the proof can of course be obtained from the authors upon request. The functional forms of $\hat{\gamma}$, $\hat{c}_1$ and $\hat{c}_2$ are $\hat{\gamma} = \frac{\delta}{2c_c+2\delta-\delta^2} \hat{c}_1 = \frac{2\delta(c_c+\delta(1-\delta))}{\delta(4\phi-\delta(2-\delta+3\phi))-2c_c(\delta-2\phi)}$ and $\hat{c}_2 = \frac{2(c_c+\delta(1-\delta))(2c_c\gamma-\delta(1-(2-\delta)\gamma))}{(2c_c+(2-\delta)\delta)(\delta+2c_c\gamma+(2-\delta)\delta\gamma)-(2c_c(2+\delta\gamma)+\delta(4-3\delta+(2-\delta)\delta\gamma))\phi}$.

Proof of Lemma 2

We first show that the IRs profit is concave in her decision variable p_r. The profit function of the IR is given by $\Pi^{IR}_{prop}(p_r|p_n, w_s) = (p_r - c_r - c_c q_r)q_r$. The second derivative of this function with respect to p_r is $\frac{\partial^2 \Pi^{IR}_{prop}(p_r|p_n,w_s)}{\partial^2 p_r} = -\frac{2(c_c+\delta(1-\delta))}{(1-\delta)^2\delta^2} < 0$. Thus, the optimal response of the IR to the OEM's decisions is given by the unique maximizer of her lagrangian function, which is given by $\mathcal{L}^{IR}(p_r, \lambda, \lambda_2) = \Pi^{IR}_{prop}(p_r|p_n, w_s) - \lambda(q_r - \gamma q_n) + \lambda_2 q_r$. Thus we get $p_r = \frac{\delta((1-\delta)(1+\delta\gamma)\lambda-(1-\delta)\lambda_2+2c_c p_n+(1-\delta)(c\phi-\beta c\phi+\delta p_n)+w_s-\delta w_s)}{2(c_c+\delta(1-\delta))}$.

Next, we insert this result into the OEM profit function $\Pi^{OEM}_{prop}(p_n, w_s|p_r) = (p_n - c_n)q_n + (w_s - c_p)q_r - \xi\beta^{\nu}$. To check concavity of the OEM profit with respect to his decision variables p_n and w_s we compute the Hessian matrix as $\mathcal{H} = \begin{bmatrix} -1 - \frac{c_c+\delta}{c_c+\delta(1-\delta)} & \frac{\delta}{c_c+\delta(1-\delta)} \\ \frac{\delta}{c_c+\delta(1-\delta)} & -\frac{1}{c_c+\delta(1-\delta)} \end{bmatrix}$. The determinant of the matrix is given by $\det[\mathcal{H}] = \frac{2}{c_c+\delta(1-\delta)} > 0$, while the first leading minor is negative. Thus, the OEM profit is jointly concave in his decision variables. Consequently, the OEM's optimal decisions are given by the unique maximizers of his profit function. We get $p_n = \frac{1+c_n}{2}$ and $w_s = \frac{\delta-\lambda-\delta\gamma\lambda+\lambda_2-c\phi+\beta c\phi+c_p}{2} = c_p + \frac{\delta-\tilde{c}}{2} + \frac{\lambda_2-\lambda-\delta\gamma\lambda}{2}$. Now we only have to consider the four possible cases resulting from the two constraints. The case where both constraints are binding, i.e., $q_r = \gamma q_n = 0$ can be excluded since it is not interesting when there is no production at all. Moreover, it can only happen when $c_n \geq 1$, which we have ruled out by assumption. Then we are left with the three described cases. Observe first, that the price p_n is independent of the constraints. Thus we already have the proposed result. Now, let us start out with the partial remanufacturing case, i.e., the case where neither constraint is binding ($\lambda = \lambda_2 = 0$). For this case w_s simplifies to $w_s = c_p + \frac{\delta-\tilde{c}}{2}$, i.e., we have the proposed result. From the condition that in this case $0 < q_r < \gamma q_n$ we can readily obtain the two conditions $\delta \geq \frac{\tilde{c}}{c_n}$ and $c < \bar{c}_1$, where $\bar{c}_1 = \frac{2\gamma(c_c+\delta-\delta^2)}{\gamma[(2c_c+\delta-\delta^2)(1+\beta\psi)+\delta(1-\phi)(1-\beta)]+(1+\beta\psi)\delta-(1-\beta)\phi-\beta(1+\psi)}$. The remaining prices and quantities can be readily obtained by plugging in the values of p_n and w_s. Now let us move to the no remanufacturing case, i.e., $0 = q_r < \gamma q_n$. In that case $\lambda = 0$ and $\lambda_2 > 0$. Plugging these λ's into w_s and then p_n and w_s into p_r and finally, everything into q_r and solving for $q_r = 0$ we obtain $\lambda_2 = c(\beta(1 - \phi + \psi - \delta\psi) - \delta + \phi) = \tilde{c} - \delta c_n$. Since $\lambda_2 > 0$ this yields $\delta < \frac{\tilde{c}}{c_n}$. The remaining prices and quantities can again be readily obtained by plugging in the values of λ_2 and p_n. Finally, the third case, full remanufacturing, implies that $0 < q_r = \gamma q_n$, and consequently $\lambda > 0$ and $\lambda_2 = 0$. Using the same logic as in the no remanufacturing scenario, i.e., inserting these λ's into w_s and then w_s and p_n into p_r and finally everything into q_r and q_n and solving the equation $q_r = \gamma q_n$ we obtain $\lambda = \frac{c(2c_c\gamma-\phi+\delta(1+\gamma(2-\delta-\phi)))-\beta c((1+\delta\gamma)(1-\phi)+(1-2c_c\gamma-\delta(1+\gamma-\delta\gamma))\psi)-2(c_c+\delta(1-\delta))\gamma}{(1+\delta\gamma)^2}$. Inserting λ into q_r and rearranging the condition $q_r > 0$ straightforward algebra yields the two bounds $\delta \geq \frac{\tilde{c}}{c_n}$ and $c \geq \bar{c}_1$. Similarly, all the remaining prices and quantities can be computed. This concludes the proof of Lemma 2.

Proof of Proposition 1

From Lemma 2 we know that the OEM deters entry by the IR whenever $\delta c_n < \tilde{c}$. Rewriting this in terms of β we directly get $\beta > \frac{\delta-\phi}{1-\phi+(1-\delta)\psi}$.

Proof of Proposition 2

From Lemmas 1 and 2 we know that the region where the OEM deters entry by the IR is always larger when there is proprietary content in the product. Thus, we now only need to compare the profits for the *no remanufacturing* cases with and without proprietary parts. In the model with proprietary parts, the OEM's associated profit is given by $\Pi^{OEM}_{prop} = \frac{(1-c_n)^2}{4} - F$. Conversely, in the model without proprietary parts, the OEM's profit is given by $\Pi^{OEM}_{gen} = \frac{(1-c)^2}{4} - \frac{\delta^4(1-c)^2}{(8c_c+8\delta-6\delta^2)^2}$. The OEM prefers introducing proprietary parts whenever $\Pi^{OEM}_{prop} > \Pi^{OEM}_{gen}$. Inserting the profit functions and rearranging for β yields the proposed result.

Proof of Lemma 3

The logic of the proof follows along exactly the same lines as in Lemma 2. The detailed exposition can be obtained from the authors upon request. The functional form of $\bar{c}_3$ is $\bar{c}_3 = \frac{(\alpha c_c+\delta(1-\delta))\gamma}{\delta+\alpha c_c\gamma+\delta\gamma-\beta(1+\delta\gamma)(1-\phi)-(1+\delta\gamma)\phi-\beta(1-\delta-\alpha c_c\gamma)\psi}$.

Proof of Lemma 4

The proof is straightforward. Simple algebra and rearrangements of terms in the condition $\bar{c}_3 \leq \bar{c}_1$ yield the proposed result.

Proof of Proposition 3

Under the condition $\delta \geq \frac{\tilde{c}}{c_n}$ we know from Lemmas 2 and 3 that either partial or full remanufacturing will take place under IR and OEM remanufacturing, respectively. Let us first consider the case where $\alpha \leq 2 + \frac{\delta(1-\delta)}{c_c}$. Lemma 4 informs us that whenever $\alpha \leq 2 + \frac{\delta(1-\delta)}{c_c}$ the OEM will switch from partial to full remanufacturing in a cost environment where the IR would stick with partial remanufacturing, i.e., $\bar{c}_3 \leq \bar{c}_1$. Thus, we compare three different scenarios:

(i) $c \leq \bar{c}_3$ – both IR and OEM would perform partial remanufacturing.
(ii) $\bar{c}_3 < c \leq \bar{c}_1$ – the OEM remanufactures fully while the IR would remanufactures partially.
(iii) $\bar{c}_1 < c$ – both IR and OEM would perform full remanufacturing.

In scenario (i) we compare $q_r = \frac{\delta c_n-\tilde{c}}{4(c_c+\delta(1-\delta))}$ for IR partial remanufacturing from Table 3, with $q_r = \frac{\delta c_n-\tilde{c}}{2(\alpha c_c+\delta(1-\delta))}$ for OEM partial remanufacturing from Table 9. We observe that the numerators are identical in both cases. Thus, we only need to compare the denominators. OEM remanufacturing is larger than IR remanufacturing when the associated denominator of OEM q_r is smaller than the denominator of the IR q_r, formally $2(\alpha c_c + \delta(1-\delta)) \leq 4(c_c + \delta(1-\delta))$. Simple algebra yields $\alpha \leq 2 + \frac{\delta(1-\delta)}{c_c}$, the proposed result. For scenarios (ii) and (iii), the result is found analogously.

Let us now turn to the case $\alpha > 2 + \frac{\delta(1-\delta)}{c_c}$. In that case we know from Lemma 4 that $\bar{c}_3 > \bar{c}_1$. Thus we need to consider the following three scenarios:

(i) $c \leq \bar{c}_1$ – both IR and OEM would perform partial remanufacturing.
(ii) $\bar{c}_1 < c \leq \bar{c}_3$ – the IR remanufactures fully while the OEM remanufactures partially.
(iii) $\bar{c}_3 < c$ – both IR and OEM would perform full remanufacturing.

In an analogous fashion to above, comparing the remanufacturing quantities of the two firms for each scenario yields the proposed result. Specifically, we find that only in scenario (iii) does OEM remanufacturing exceed IR remanufacturing.

Appendix B. Consumer surplus derivation

In line with the assumptions made for deriving demand functions (5), we define the consumer surplus to be the cumulative difference between a consumer's willingness to pay for the chosen product (new or remanufactured) and the corresponding price. The assumptions are as follows (see, e.g., Debo et al., 2005; Oraiopoulos et al., 2012; Souza, 2013): the willingness to pay for new products θ is uniformly distributed among the consumers with support $U[0, 1]$. The willingness to pay for a remanufactured product is a constant fraction δ of that one for a new product, i.e., $\delta\theta$. Thus, for any customer the net utilities for buying a new, remanufactured, or no product are $U_n = \theta - p_n$, $U_r = \delta\theta - p_r$, $U_z = 0$, respectively, and consumer surplus (for a standardized market size of 1) becomes $\Upsilon = \int_0^1 \max\{U_n, U_r, U_z\}\, d\theta$. Switching points for θ between not buying and buying remanufactured and between buying remanufactured and new items, $0 \leq \theta_{zr} < \theta_{rn} < 1$ are given by $\theta_{zr} = \frac{p_r}{\delta}$, $\theta_{rn} = \frac{p_n-p_r}{1-\delta}$ (Abbey et al., 2017), and therefore consumer surplus becomes:

$$\Upsilon = \int_{\theta_{rn}}^{1} (\theta - p_n)\, d\theta + \int_{\theta_{zr}}^{\theta_{rn}} (\delta\theta - p_r)\, d\theta = \left[\frac{1}{2}\theta^2 - p_n\theta\right]_{\theta_{rn}}^{1} + \left[\frac{\delta}{2}\theta^2 - p_r\theta\right]_{\theta_{zr}}^{\theta_{rn}} = q_n\left(1 - p_n - \frac{q_n}{2}\right) + \frac{\delta q_r^2}{2}$$

Appendix C. Alternative competitive settings

C.1. Quantity competition

In this model variant, we keep the sequence of events but replace the price decisions by quantity decisions, i.e., after deciding on the proprietary content β of the product, the OEM sets the wholesale price for proprietary spare parts w_s and the quantity of new products q_n to sell. Finally, the IR decides on the quantity of remanufactured products q_r. Solving the quantity competition, we obtain the following results, structured analogously to Lemma 2.

Table C.10
Equilibrium prices and quantities in all three strategy regions.

Strategy region	R1 No remanufacturing	R2 Partial remanufacturing	R3 Full remanufacturing
w_s	$\geq c_p + \frac{\delta(1-c_n)}{2}$	$c_p + \frac{\delta-\tilde{c}}{2}$	$c_p + \frac{(\delta+2c_c\gamma+2\delta\gamma)(1-c_n)}{2(1+\delta\gamma)}$
p_n	$\frac{1+c_n}{2}$	$\frac{1+c_n}{2}$	$\frac{1+c_n}{2}$
p_r	n.a.	$\delta p_n - \frac{\delta(1-\delta)(\delta c_n-\tilde{c})}{2(2c_c+2\delta-\delta^2)}$	$\delta p_n - \frac{\gamma\delta(1-\delta)(1-c_n)}{2(1+\delta\gamma)}$
q_n	$\frac{1-c_n}{2}$	$\frac{1-c_n}{2} - \frac{\delta(\delta c_n-\tilde{c})}{2(2c_c+2\delta-\delta^2)}$	$\frac{1-c_n}{2} - \frac{\gamma\delta(1-c_n)}{2(1+\delta\gamma)}$
q_r	0	$\frac{\delta c_n-\tilde{c}}{4(c_c+\delta(1-\delta))}$	γq_n

$\bar{c}_1^Q = \frac{(2c_c+(2-\delta)\delta)\gamma}{\delta+2c_c\gamma+2\delta\gamma-\beta(1+\delta\gamma)(1-\phi)-(1+\delta\gamma)\phi-\beta(1-\delta-2c_c\gamma-\delta\gamma)\psi}$

Table C.11
Equilibrium prices and quantities in all three strategy regions.

Strategy region	R1 No remanufacturing	R2 Partial remanufacturing	R3 Full remanufacturing
w_s	$\geq c_p + \frac{\delta(1-c_n)}{2}$	$c_p + \frac{\delta-\tilde{c}}{2} - \frac{(\delta c_n-\tilde{c})(2c_c+\delta(1-\delta))^2}{2[(2c_c+2-\delta-\delta^2)^2-4(1-\delta^2)(1-3\delta)]}$	$c_p + \frac{\delta(1-c_n)}{2} + \frac{2(1-c_n)(1-\delta)(c_c+\delta(1-\delta))\gamma}{2c_c(1+\gamma)+(1-\delta)(2+\delta+3\delta\gamma)}$
p_n	$\frac{1+c_n}{2}$	$\frac{1+c_n}{2} + \frac{(\delta c_n-\tilde{c})(1-\delta)(2c_c+\delta(1-\delta))}{(2c_c+2-\delta-\delta^2)^2-4(1-\delta^2)(1-3\delta)}$	$\frac{1+c_n}{2} + \frac{(1-c_n)(1-\delta)(2c_c+\delta(1-\delta))\gamma}{2[2c_c(1+\gamma)+(1-\delta)(2+\delta+3\delta\gamma)]}$
p_r	n.a.	$\delta\frac{1+c_n}{2} - \frac{2\delta(1-\delta)^2(\delta c_n-\tilde{c})}{(2c_c+2-\delta-\delta^2)^2-4(1-\delta^2)(1-3\delta)}$	$\delta\frac{1+c_n}{2} - \frac{(1-c_n)(1-\delta)^2\delta\gamma}{2c_c(1+\gamma)+(1-\delta)(2+\delta+3\delta\gamma)}$
q_n	$\frac{1-c_n}{2}$	$\frac{1-c_n}{2} - \frac{(\delta c_n-\tilde{c})(2c_c+3\delta(1-\delta))}{(2c_c+2-\delta-\delta^2)^2-4(1-\delta^2)(1-3\delta)}$	$\frac{1-c_n}{2} - \frac{(1-c_n)(2c_c+3\delta(1-\delta))\gamma}{2[2c_c(1+\gamma)+(1-\delta)(2+\delta+3\delta\gamma)]}$
q_r	0	$\frac{(\delta c_n-\tilde{c})(2c_c+2-\delta-\delta^2)}{(2c_c+2-\delta-\delta^2)^2-4(1-\delta^2)(1-3\delta)}$	γq_n

$$\bar{c}_1^N = \frac{(4c_c^2+(1-\delta)^2\delta(8+\delta)+4c_c(2-\delta(1+\delta)))\gamma}{(4c_c^2+(1-\delta)^2\delta(8+\delta)+4c_c(2-\delta(1+\delta)))\gamma+2(2c_c(1+\gamma)+(1-\delta)(2+\delta+3\delta\gamma))(\delta-\beta(1-\phi)-\phi)-\beta(2c_c+(1-\delta)(2+\delta))(2-2c_c\gamma-\delta(2+\gamma-\delta\gamma))\psi}$$

Lemma 5. *Characteristics of the equilibrium regions for a fixed value of β are given in Table C.10. Given new production is profitable using proprietary parts, there exists a threshold value for the marginal production cost of a new product, $\bar{c}_1^Q$, and the equilibrium regions can be described as follows:*
No remanufacturing. If $\delta c_n < \tilde{c}$, the IR does not enter the market and the OEM acts as a monopolist.
Partial remanufacturing. If $\delta c_n \geq \tilde{c}$ and $c < \bar{c}_1^Q$, the IR enters the market but does not remanufacture all available cores.
Full remanufacturing. If $\delta c_n \geq \tilde{c}$ and $c \geq \bar{c}_1^Q$, the IR enters the market and remanfactures all available cores.

The proof of Lemma 5 follows along the same lines as the proof of Lemma 2 and is omitted here. It can be obtained from the authors upon request.

These results confirm the structural similarity of the price and quantity competition models. The bound for R1 (no remanufacturing) is identical to the bound in our original setting (see Lemma 2). Comparing the thresholds $\bar{c}_1^Q$ and $\bar{c}_1$ we find that $\bar{c}_1^Q > \bar{c}_1$. Thus, under quantity competition, the region where partial remanufacturing is optimal is larger.

C2. Simultaneous market price decisions

In this model variant, we abstract from the Stackelberg setting and consider a situation where the OEM and the IR set their market prices p_n and p_r simultaneously. The associated sequence of events is as follows: Initially, the OEM decides on the proprietary content β of the product. Then the OEM sets the wholesale price for proprietary spare parts w_s. Finally, the OEM and the IR simultaneously decide on p_n and p_r, respectively. Solving the third stage as a Nash-game, we obtain the following results, which are structured analogously to Lemma 2.

Lemma 6. *Characteristics of the equilibrium regions for a fixed value of β are given in Table C.11. Given new production is profitable using proprietary parts, there exists a threshold value for the marginal production cost of a new product, $\bar{c}_1^N$, and the equilibrium regions can be described as follows:*
No remanufacturing. If $\delta c_n < \tilde{c}$, the IR does not enter the market and the OEM acts as a monopolist.
Partial remanufacturing. If $\delta c_n \geq \tilde{c}$ and $c < \bar{c}_1^N$, the IR enters the market but does not remanufacture all available cores.
Full remanufacturing. If $\delta c_n \geq \tilde{c}$ and $c \geq \bar{c}_1^N$, the IR enters the market and remanfactures all available cores.

The proof of Lemma 6 follows along the same lines as the proof of Lemma 2 and is omitted here. It can be obtained from the authors upon request. These results confirm the structural similarity of the price and quantity competition models. The bound for R1 (no remanufacturing) is identical to the bound in our original setting (see Lemma 2). Comparing the thresholds $\bar{c}_1^N$ and $\bar{c}_1$ we find that $\bar{c}_1^N < \bar{c}_1$. Thus, under simultaneous market pricing decisions, the region where partial remanufacturing is optimal is smaller.

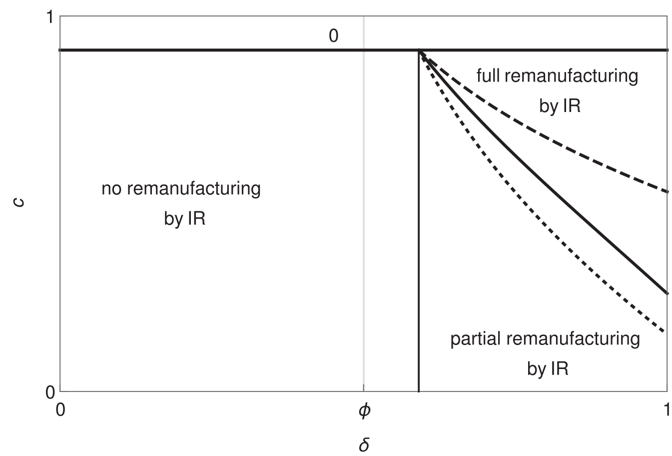

Fig. C5. Strategy regions in the case of an OEM using proprietary parts, under different types of competition: Stackelberg price competition (bold), Stackelberg quantity competition (dashed), Nash price competition (dotted).

To conclude, Fig. C5 visualizes the variations in the strategy space implied by the different types of competition, clearly highlighting the structural similarity of the results.

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